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Title: The Regenerative Amplifier Free-Electron Laser (RAFEL)

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THE REGENERATIVE AMPLIFIER FREE-ELECTRON LASER (RAFEL)

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Colloquium presented at the Naval Research Laboratory
21 November 2012

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OUTLINE

- Introduction
  - RAFEL Configuration
  - Differences with Low-Gain Oscillators
- Numerical Formulation
  - MEDUSA
  - OPC
- Examples of Validation
  - BNL Tapered-Wiggler Amplifier
  - SPARC SASE FEL
  - JLAB IR-Upgrade Oscillator
- Nominal RAFEL Simulation
  - Properties
  - Differences with Low-Gain Oscillators
- LANL RAFEL Experiment
- X-Ray RAFEL Proposal

WHAT IS A RAFEL?

- A RAFEL is a Low-Q oscillator with a High-Gain Wiggler
  - Many differences compared with a typical High-Q, Low-Gain oscillator

	Low-Gain Oscillator	High-Gain RAFEL
Resonance	$2\gamma_z^2 k_w c[1 - 1/(2.4N_w)]$	$2\gamma_z^2 k_w c$
Detuning Range	Narrow	Broad
Linewidth	$1/N_w$	ρ
Efficiency	$1/(2.4N_w)$	ρ
Slippage	$N_w\lambda$	$N_w\lambda/3$
Transverse Mode Structure	Determined by the Resonator Modes	Determined by the Wiggler Interaction

- Since the RAFEL out-couples a large fraction of the pulse energy on each pass, the mirror loading is relatively small
  - Advantageous for high-power FELs and (possibly) x-ray FELs

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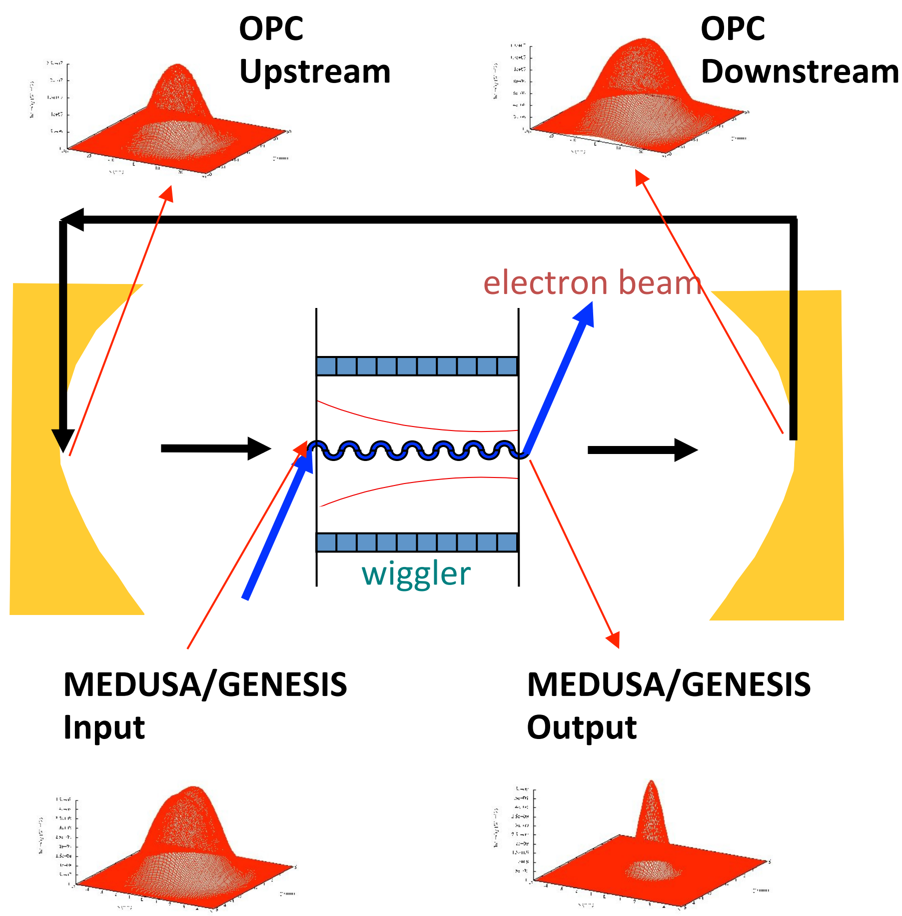
THE MEDUSA FAMILY OF CODES

Property \ Code	ARACHNE	WIGGLIN	CHIFEL	MEDUSA
Creation	1985	1987	1995	1995
E & M Modes	Cylindrical Waveguide	Rectangular Waveguide	Coaxial Waveguide	Gaussian Optical
Wiggler Models	Helical	Planar	CHI	Planar or Helical
Polychromatic	Yes	No	No	Yes
Prebunched Beam	No	Yes	No	Yes
Time-Dependence (4D)	No	No	No	Yes
Parallelized	No	No	No	Yes
Start-Up from Noise	No	No	No	Yes
Additional B-Fields	No	No	No	Yes

AMPLIFIER/OSCILLATOR PROCEDURE

- Amplifiers/SASE can be simulated by a single pass through the simulation code
- Oscillators require multiple passes through the wiggler and resonator
  - Optics Propagation Code (OPC) propagates the field around the resonator and hands off the complex phase front at the wiggler entrance to MEDUSA/GENESIS

- MEDUSA writes the phase front at the output of the wiggler directly into the input file for OPC, but uses a translator to decompose the complex phase front at the wiggler entrance from OPC back into Gaussian optical modes and then write a new input file
- GENESIS uses the same grid (size and number of mesh points) as used in OPC so no translators are necessary



TAPERED WIGGLER MOPA BNL

- Taper experiment performed at the SDL at BNL
  - Beam energy on-resonance
- NISUS wiggler can be tapered by segments
  - Start taper point at 7.0 m
  - Optimal slope corresponds to – 4% taper over 3 m
- Seed laser power optimized the interaction for the start taper point

Energy (on resonance)	100.86 MeV
Bunch Charge	350 pC
Bunch Duration	1-2 psec
Normalized Emittance	4 mm-mrad
Energy Spread	0.1%
Wiggler Period	3.89 cm
Wiggler Length	10 m
Wiggler Amplitude	3 kG
Start Taper Point	7.0 m
Taper Amount	− 4.0%
Seed Wavelength	793.5 nm
Seed Power	10 kW
Seed Duration	6 psec

PRL **103**, 154801 (2009) PHYSICAL REVIEW LETTERS week ending 9 OCTOBER 2009

Efficiency and Spectrum Enhancement in a Tapered Free-Electron Laser Amplifier

X. J. Wang,[1] H. P. Freund,[2] D. Harder,[1] W. H. Miner, Jr.,[2] J. B. Murphy,[1] H. Qian,[1] Y. Shen,[1] and X. Yang[1]
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(Received 12 May 2009; published 7 October 2009)

We report the first experimental characterization of efficiency and spectrum enhancement in a laser-seeded free-electron laser using a tapered undulator. Output and spectra in the fundamental and third harmonic were measured versus distance for uniform and tapered undulators. With a 4% field taper over 3 m, a 300% (50%) increase in the fundamental (third harmonic) output was observed. A significant improvement in the spectra with the elimination of sidebands was observed using a tapered undulator. The experiment is in good agreement with predictions using the MEDUSA simulation code.

DOI: 10.1103/PhysRevLett.103.154801 PACS numbers: 41.60.Cr, 52.59.Rz

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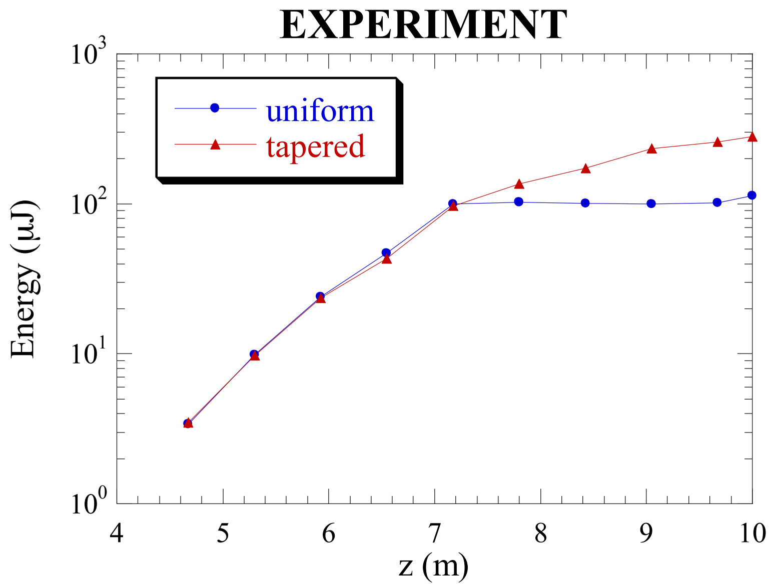
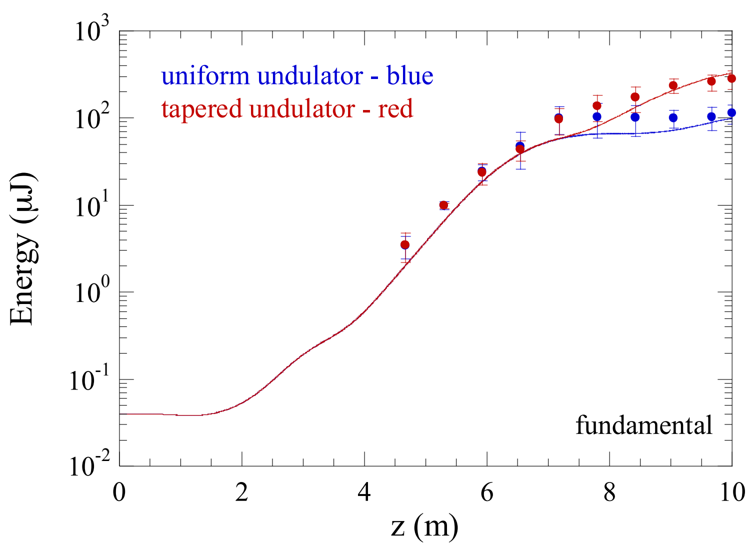
UNIFORM vs TAPERED WIGGLER

- The experiment found an increase by a factor of about 3 of the uniform wiggler output (113 ± 28 μJ) in comparison with the tapered wiggler output (283 ± 68 μJ)





- MEDUSA simulations were in substantial agreement over the entire length of the NISUS wiggler
  - uniform wiggler – 100 μJ
  - tapered wiggler – 336 μJ

SPARC SASE EXPERIMENT: FRASCATI

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 060712 (2011)

Self-amplified spontaneous emission for a single pass free-electron laser

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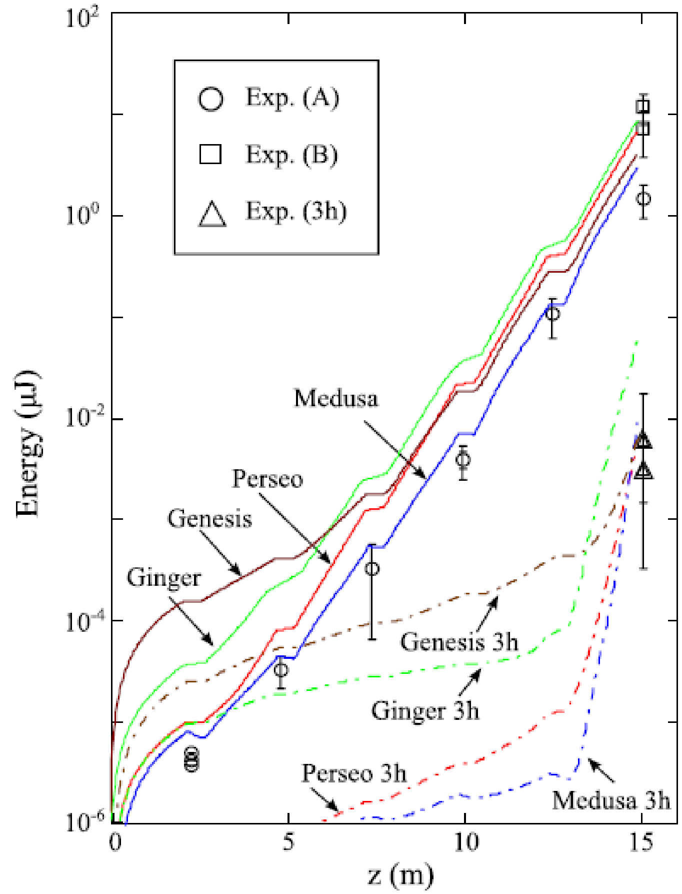
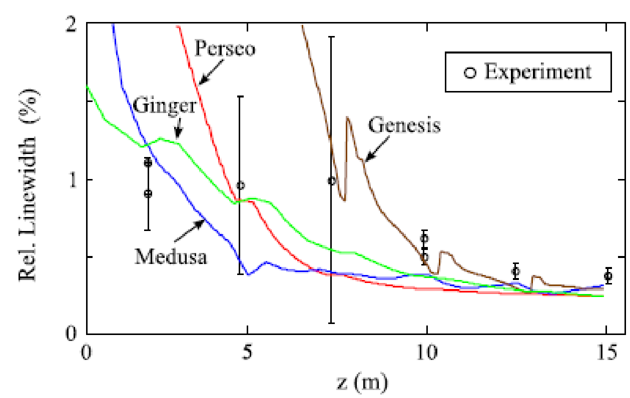
- MEDUSA, GENESIS, GINGER, and PERSEO were compared with data
- GENESIS & GINGER over-predicted both the fundamental and 3rd harmonic power in the start-up regime
  - Attributed to larger HOM production at the start-up
  - Even 3rd harmonic powers at the start-up were higher than observed for the fundamental
- PERSEO & MEDUSA were closer to the data over the entire range
- Discrepancies seen between the linewidth predicted by GENESIS versus the other codes and the experiment
  - All codes were in good agreement with the linewidth after about 10 m





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JLAB IR-UPGRADE EXPERIMENT

PRL 103, 154801 (2009) PHYSICAL REVIEW LETTERS week ending 9 OCTOBER 2009

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(Received 12 May 2009; published 7 October 2009)

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DOI: 10.1103/PhysRevLett.103.154801 PACS numbers: 41.60.Cr, 52.59.Rz

- MEDUSA/OPC validated for the 10-kW Upgrade Experiment at JLab

Electron Beam	
Beam Energy:	115 MeV
Bunch Charge:	115 pC
Bunch Length:	390 fsec
Bunch Frequency:	74.85 MHz
Emittance:	9 mm-mrad (wiggle plane)
	7 mm-mrad
Energy Spread:	0.3%
Wiggler	
Period:	5.5 cm
Amplitude:	3.75 kG
Length:	30 periods
Radiation/Resonator	
Wavelength:	1.6 microns
Resonator Length:	32 m
Rayleigh Range:	0.75 m
Out-Coupling:	21% (transmissive)

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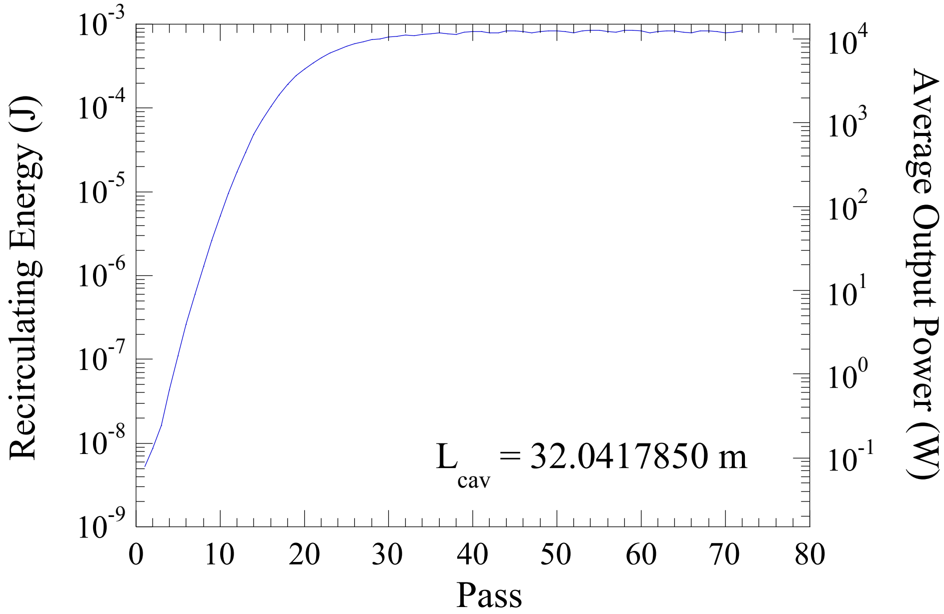
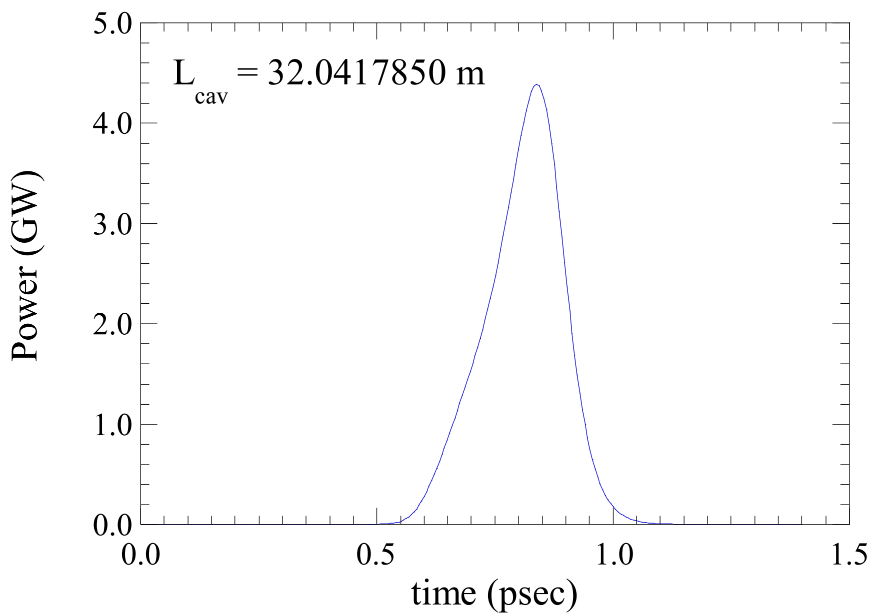
PULSE GROWTH &TEMPORAL SHAPE

Typical simulations show a region of exponential growth that rolls over to reach a long-term steady state. Oscillations in the pulse energy/power are seen, and correspond to an oscillation in the position of the more waist (more later).





The pulse shapes are found to be smooth and distorted from a symmetric pulse due to slippage and the cavity tuning.

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CAVITY TUNING & PERFORMANCE

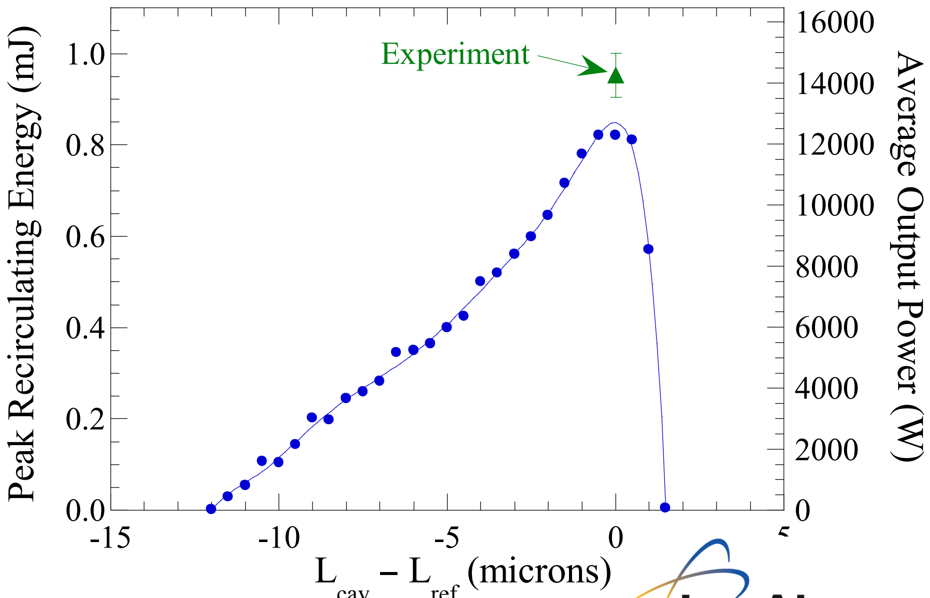
• Comparison of the cavity tuning curve with the observed optimal cavity tuning and power show good agreement. **The experiment records 14.3 ± 0.72 kW, and the simulation finds 12.3 kW** at the optimal cavity length.

• No complete cavity tuning curve is available from the experiment, but there is agreement as to the width of the tuning curve and the shape.

  - **The width seen in simulation and the experiment is about 12-13 microns.**
  - **The shape of the tuning curve is not sharply peaked but, rather, is triangular in both the experiment and the simulation.**

• The exact optimal cavity length in the experiment is not known. In addition, the zero-detuning condition ($L_{cav} = \upsilon_{gr}/2f_{rep}$) is not a precise calculation because the group velocity in the wiggler is not known.

  - Because of this, we use L_{ref} to correspond to the optimal cavity length found in simulation.



A 2.2-μm RAFEL DESIGN

Electron Beam	
Energy	55 MeV
Bunch Charge	800 pC
Bunch Duration	1.2 psec (FW parabolic)
Repetition Rate	87.5 MHz
Emittance	15 mm-mrad
Energy Spread	0.25%
Wiggler	**Two-Plane Focusing**
Period	2.4 cm
K_{rms}	1.03 – 1.11
Length	100 Periods
Resonator	**Concentric**
Wavelength	2.2 μm
Length	6.852 m
Radii of Curvature	3.5 m
Rayleigh Range	0.5 m
Hole Radius	5.0 mm
Out-Coupling	97%

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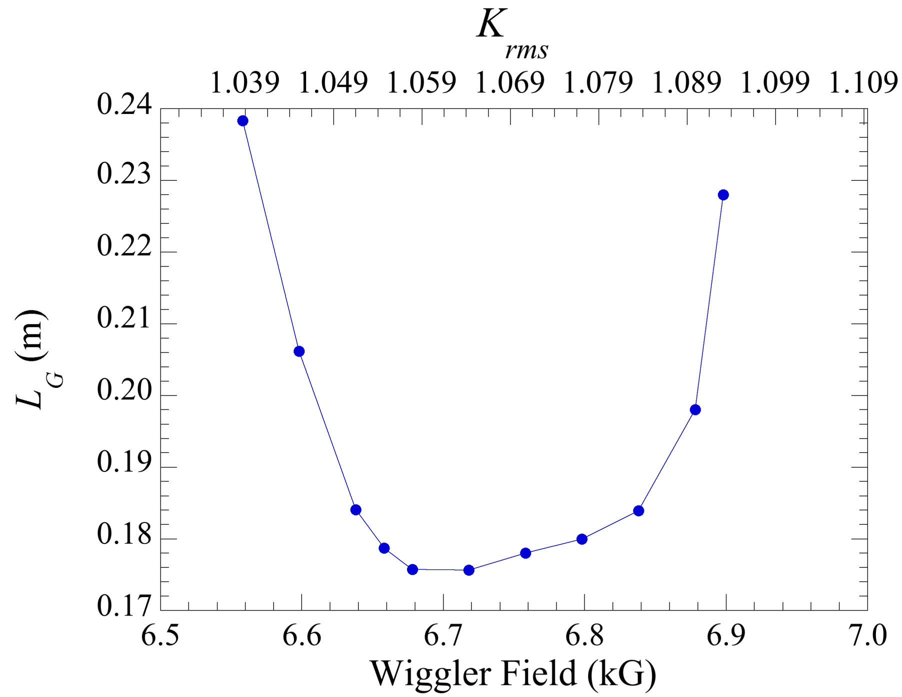
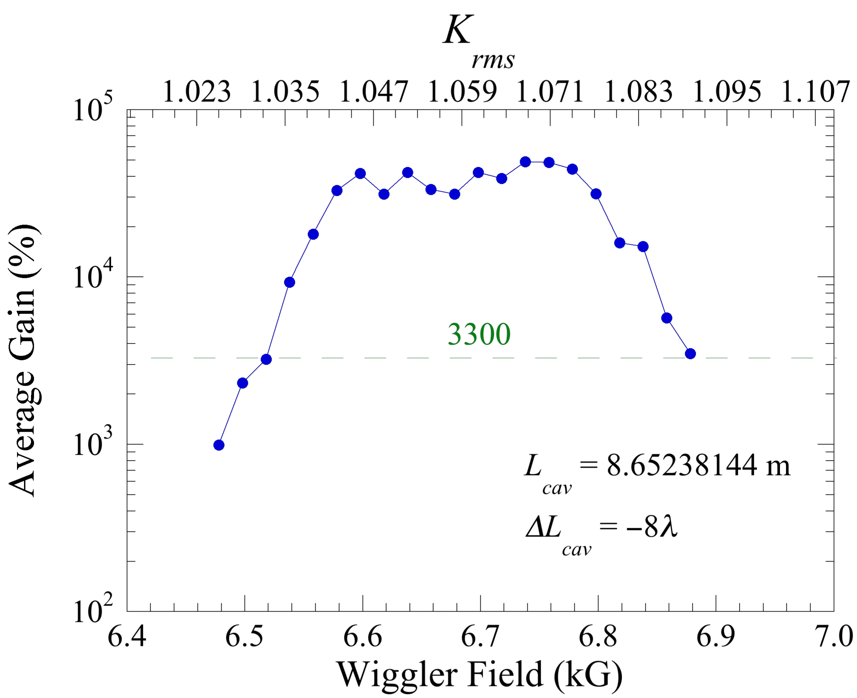
SINGLE-PASS GAIN

- The single-pass gain length is typical for the exponential (high-gain Compton) regime
  - Ming Xie analytic model predicts $L_G = 0.16$ m



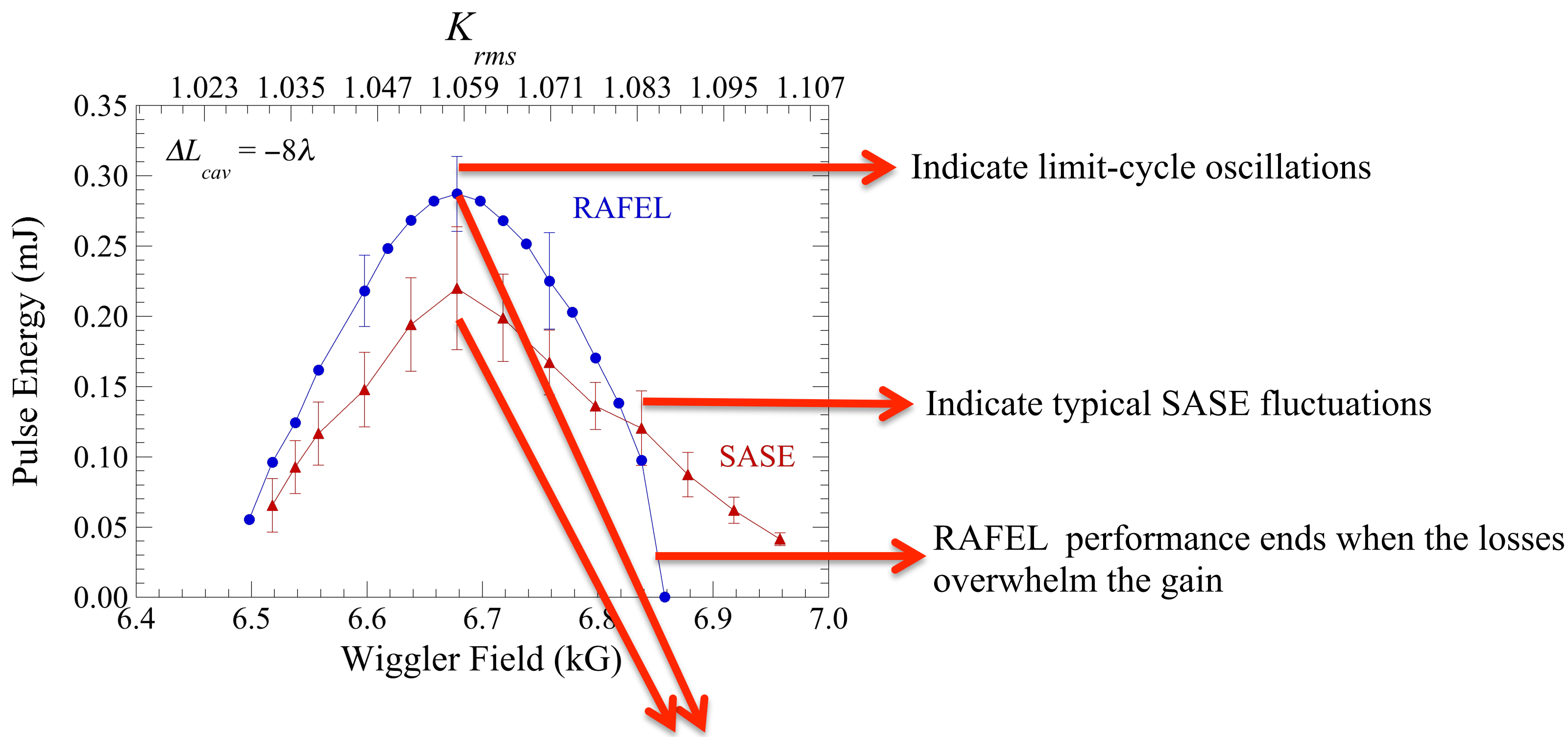


- The RAFEL can be expected to turn on when the gain exceeds the losses

$$G \geq \frac{L}{1-L} \approx 3300$$

RAFEL vs SASE

- Since the RAFEL also starts from shot-noise, it is useful to compare it with a corresponding SASE FEL (*i.e.*, all parameters the same, except that the resonator is replaced by a longer wiggler)



RAFEL and SASE FEL show peak performance at the same resonance point as evidence of the exponential growth in both configurations

SLIPPAGE IN THE HIGH-GAIN REGIME

- The group velocity in the high-gain regime can be found by implicitly differentiating the dispersion equation. In 1-D this yields

$$\frac{\upsilon_{gr}}{c} \approx \left(1 + \frac{1}{3\gamma_{||}^2}\right)^{-1}$$

- As a result, the light slips ahead of the electrons in this regime by a reduced amount

$$\tau_{slip} = \frac{N_w \lambda}{3}$$

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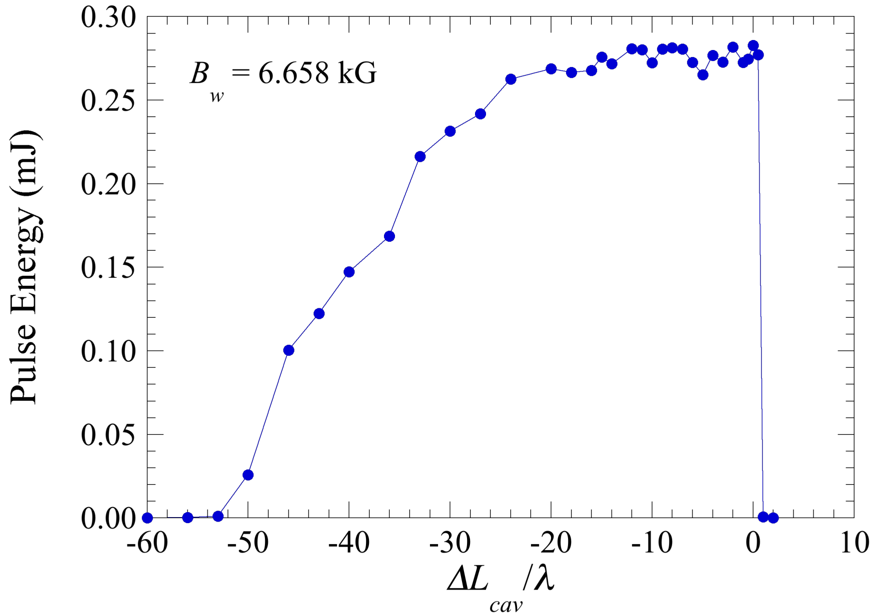
CAVITY DETUNING

- The zero detuning length corresponds to perfect synchronism between the round trip time and the electron bunch spacing. When $\upsilon_{gr} = c$ this is

$$L_0 = \frac{c}{2 f_{rep}}$$

- Since υ_{gr} is reduced in the RAFEL, synchronism is found when

$$\frac{1}{f_{rep}} = \frac{2L_{cav} - L_w}{c} + \frac{L_w}{\upsilon_{gr}} \longrightarrow L_{cav} = L_0 - \frac{N_w \lambda}{3}$$



- Since the gain is high in the RAFEL, very little re-circulated power is needed to reach saturation; hence, the detuning range is broad

LINEWIDTH

- The linewidth of a low-gain oscillator is given by

$$(\Delta\omega/\omega)_{FW} = 1/N_w = 0.01$$

- The linewidth for a SASE FEL is given by

$$(\Delta\omega/\omega)_{rms} = \rho \approx 0.0097 \longrightarrow (\Delta\omega/\omega)_{\mathrm{FWHM}} \approx 2.3\rho \approx 0.022$$

- The linewidth can be translated into a tuning range over the wiggler field

$$\left|\frac{\Delta B_w}{B_w}\right| = \frac{1+K_{rms}^2}{2K_{rms}^2}\left|\frac{\Delta\omega}{\omega}\right| \approx 0.95(\Delta\omega/\omega)$$

  - **SASE FEL:** $(\Delta B_w/B_w)_{\mathrm{FWHM}} \approx 0.021$
  - **RAFEL Simulation:** $(\Delta B_w/B_w)_{\mathrm{FWHM}} \approx 0.019$

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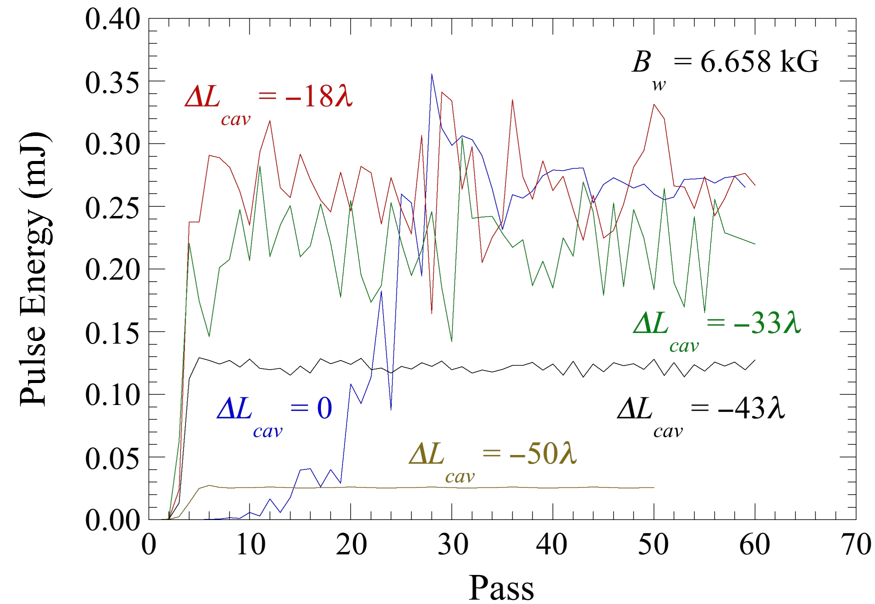
TEMPORAL PULSE EVOLUTION

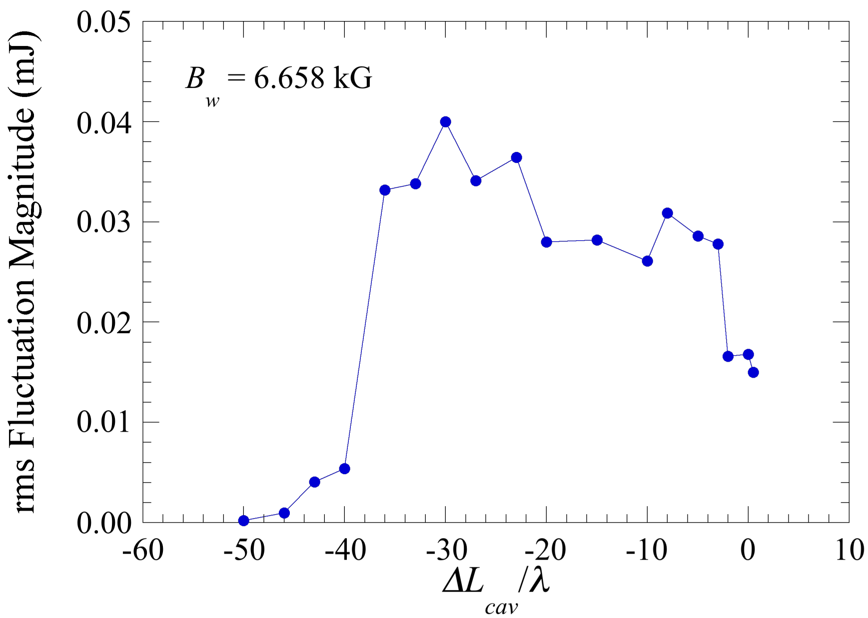
- Limit-cycle oscillations are observed in low gain oscillators with a period of about

$$\Delta\tau = -\,\tau_{slip}\,\frac{L_{cav}}{\Delta L_{cav}}$$

For RAFEL $\rightarrow$
$$\Delta\tau = -\,\frac{\tau_{roundtrip}}{2}\,\frac{N_w\lambda}{3\Delta L_{cav}} \approx -\,\tau_{roundtrip}\frac{16\lambda}{\Delta L_{cav}}$$

- Hence, the oscillations occur more rapidly in a RAFEL





- The magnitude of the oscillations vary with detuning as shown, but are relatively large over the range of detuning with the maximum output

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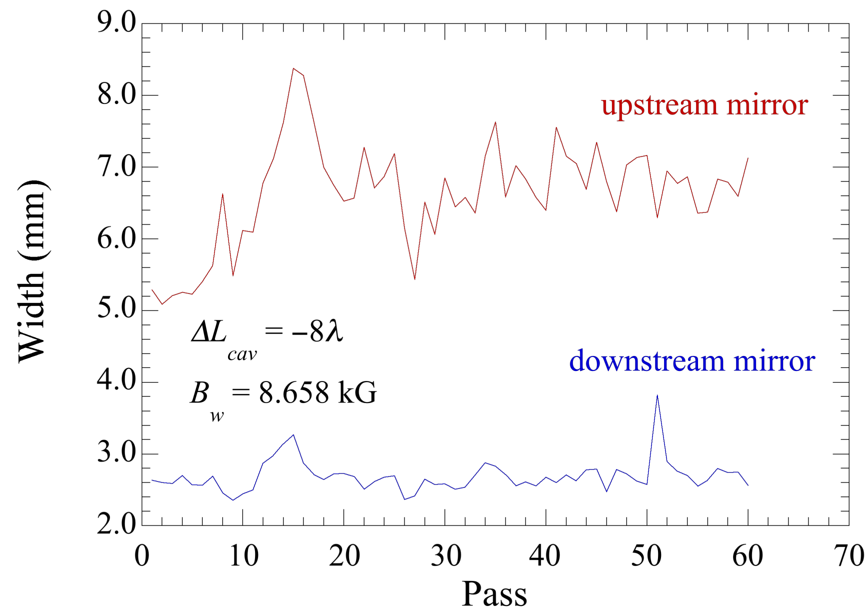
OSCILLATIONS IN THE MODE SIZE

- The limit-cycle oscillations lead to variations in the gain that, in turn, lead to variations in optical guiding
  - In the exponential regime, small variations in the growth rate can lead to large variations over the wiggler length

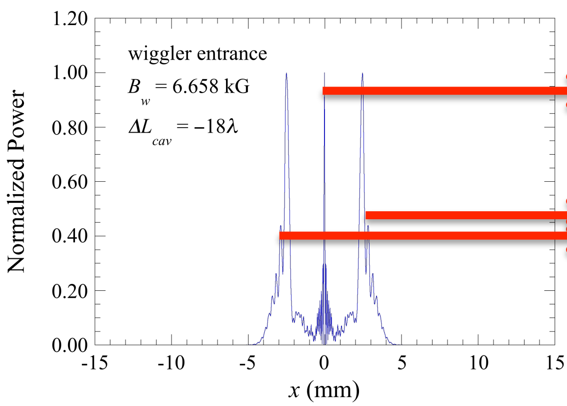


- This leads to oscillations in the mode sizes at the mirrors

- The definition of a mode waist is not well-defined due to the extended region of optical guiding

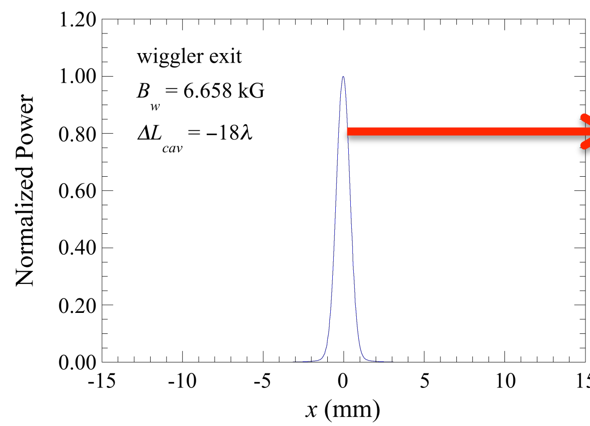
TRANSVERSE MODE STRUCTURE

- The transverse mode structure is also affected by the hole out-coupling as shown in the figures for pass 60

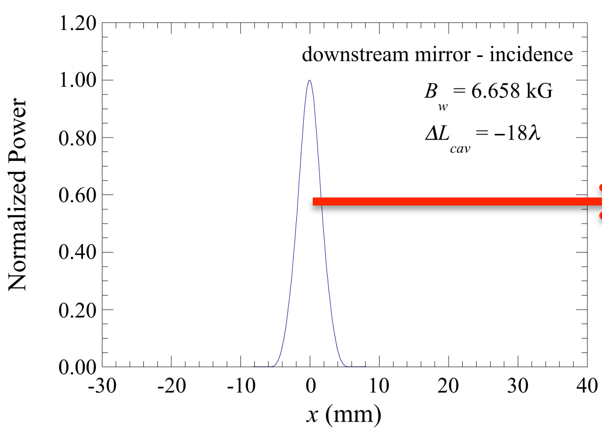


HOMs yield power in the center

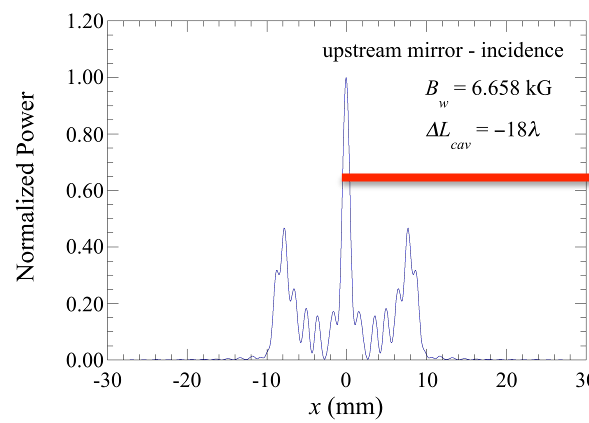
Most power in wings



Interaction amplifies on-axis mode, but HOMs are also present



Mode expands at the downstream mirror



And repeat

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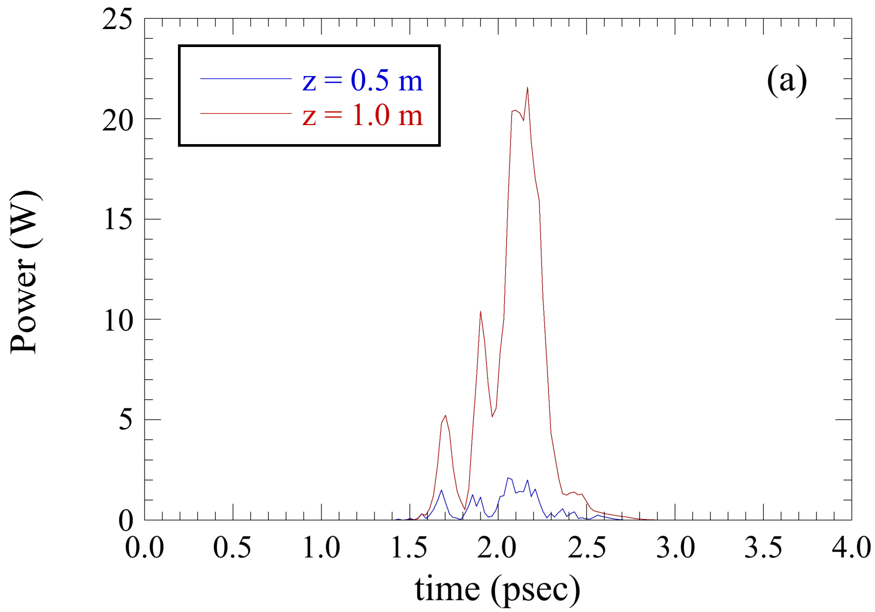
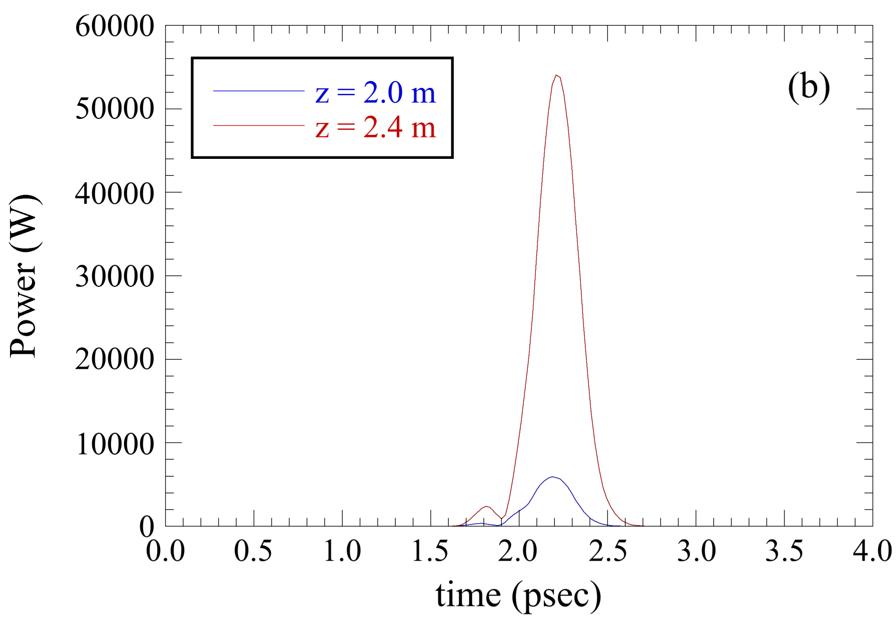
TEMPORAL COHERENCE – FIRST PASS

- The first pass shows typical SASE evolution
  - Many spikes in the start-up region
  - Temporal coherence develops over the course of the interaction





- The power doesn’t saturate on one pass, nevertheless only two spikes are left at the wiggler exit

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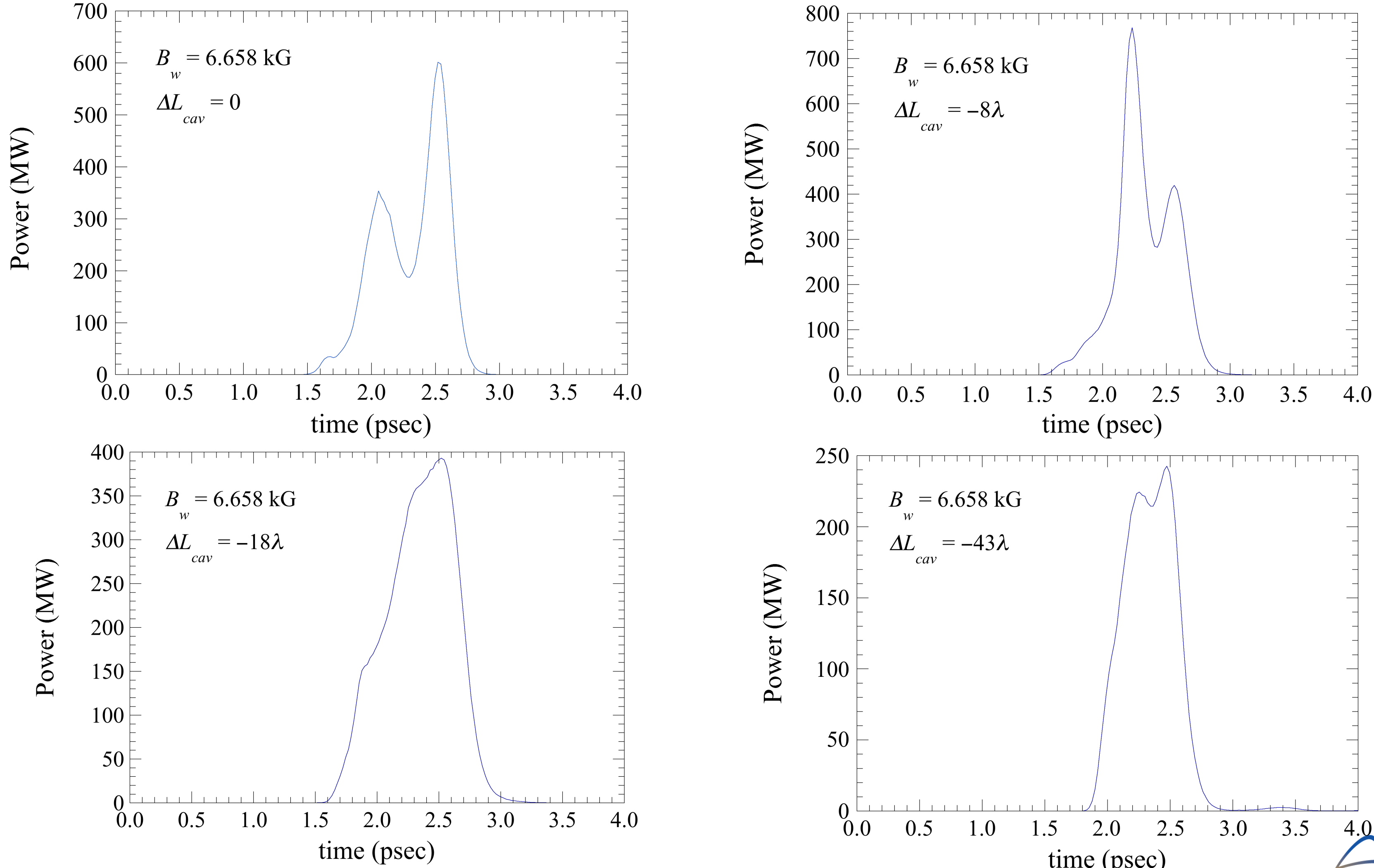
TEMPORAL COHERENCE – MULTI-PASS

- The pulse shape in the steady-state regime depends upon the detuning, but we generally do not find that the pulse coalesces into a single-spike



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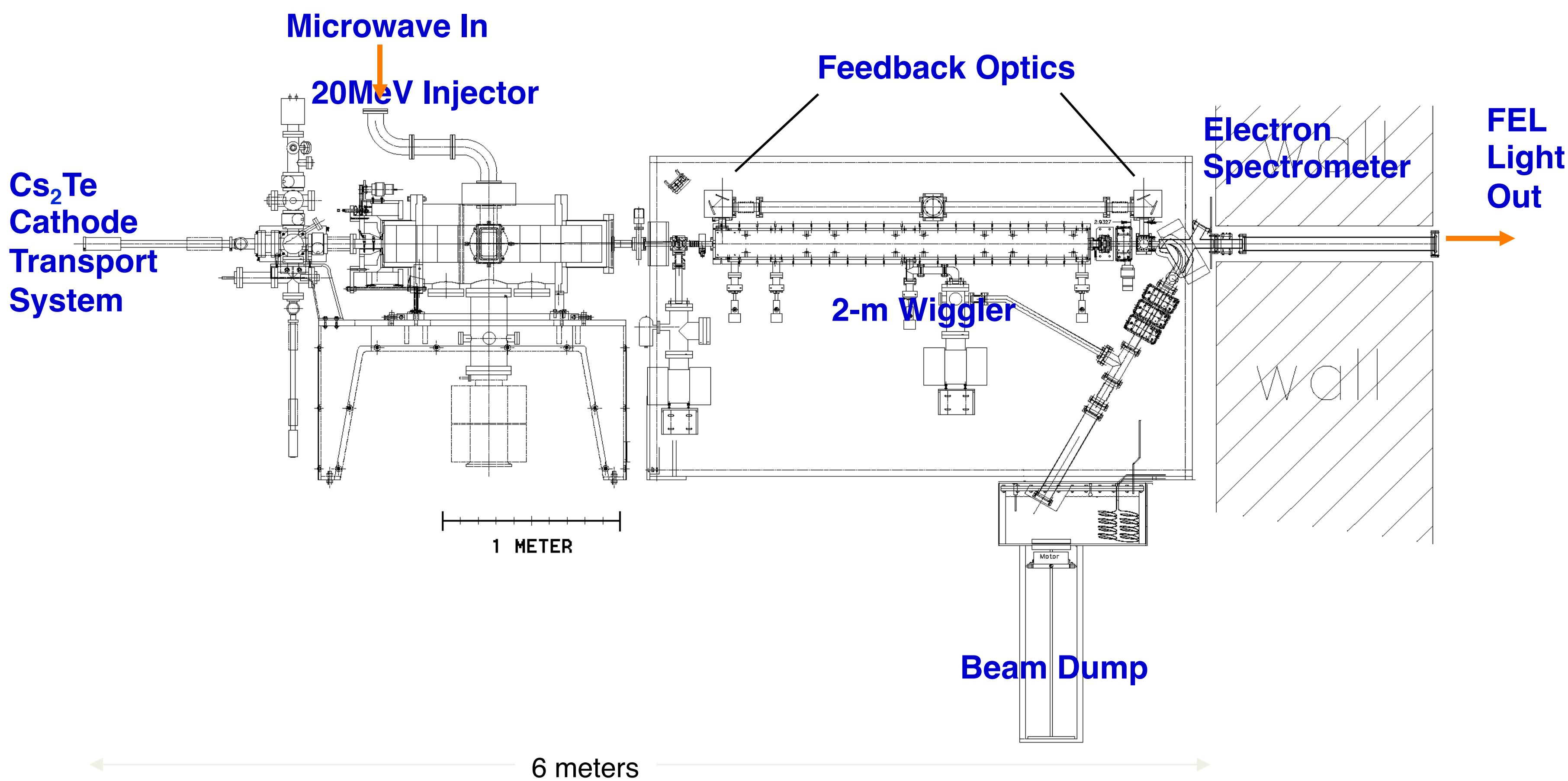
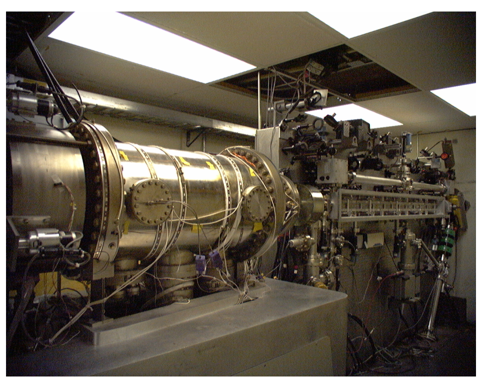
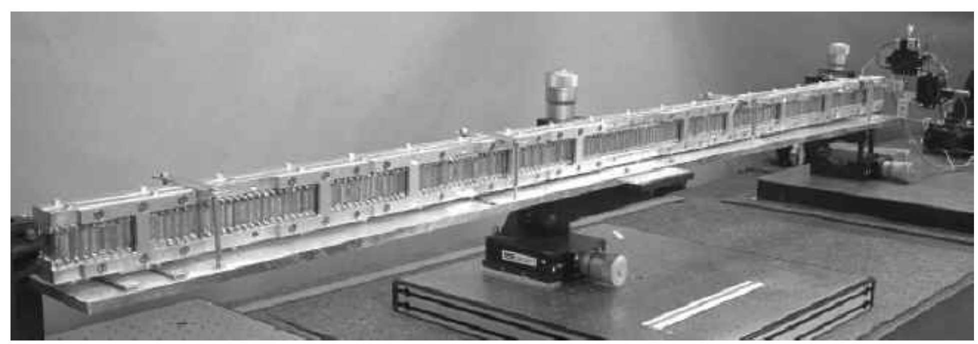
16.3 μm RAFEL EXPERIMENTAL SETUP







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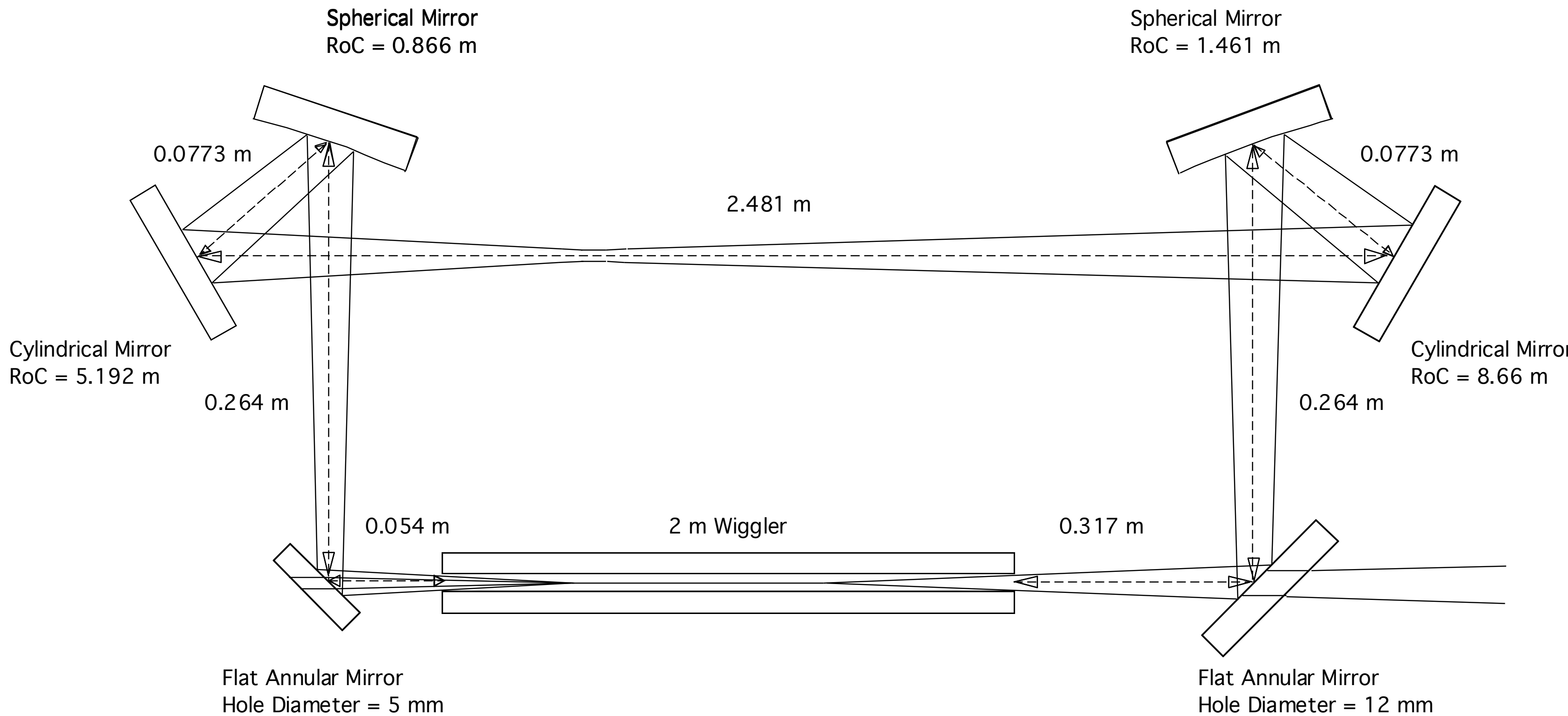
LOW-Q RING RESONATOR



- Combination of spherical/cylindrical mirrors approximates a 90^o paraboloid.
- Cavity length is twice as long as micropulse spacing (two FEL optical micropulses circulate inside the optical feedback loop).
- The zero-detuning length is 5.534631696 m (2 pulses).
  - The group velocity reduction ≈ 50 microns effect

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BEAM & WIGGLER PARAMETERS

Electron Beam	
Energy	17 MeV
Bunch Charge	2 – 5 nC
Bunch Duration	22.6 psec
Emittance	1.8 – 7.5 mm-mrad
Energy Spread	0.5%
Micropulse Repetition Rate	108 MHz
Wiggler	**Two-Plane Focusing, Tapered**
Period	2.0 cm
Peak On-Axis Field	7.0 kG
Length	100 Periods (2.0 m)
K_{rms}	0.92
Start-Taper Point	1.0 m
Taper Slope	-2.1 kG/m

- Simulations are still in the preliminary stages
  - Parameter scan needed
  - New script needs refinement

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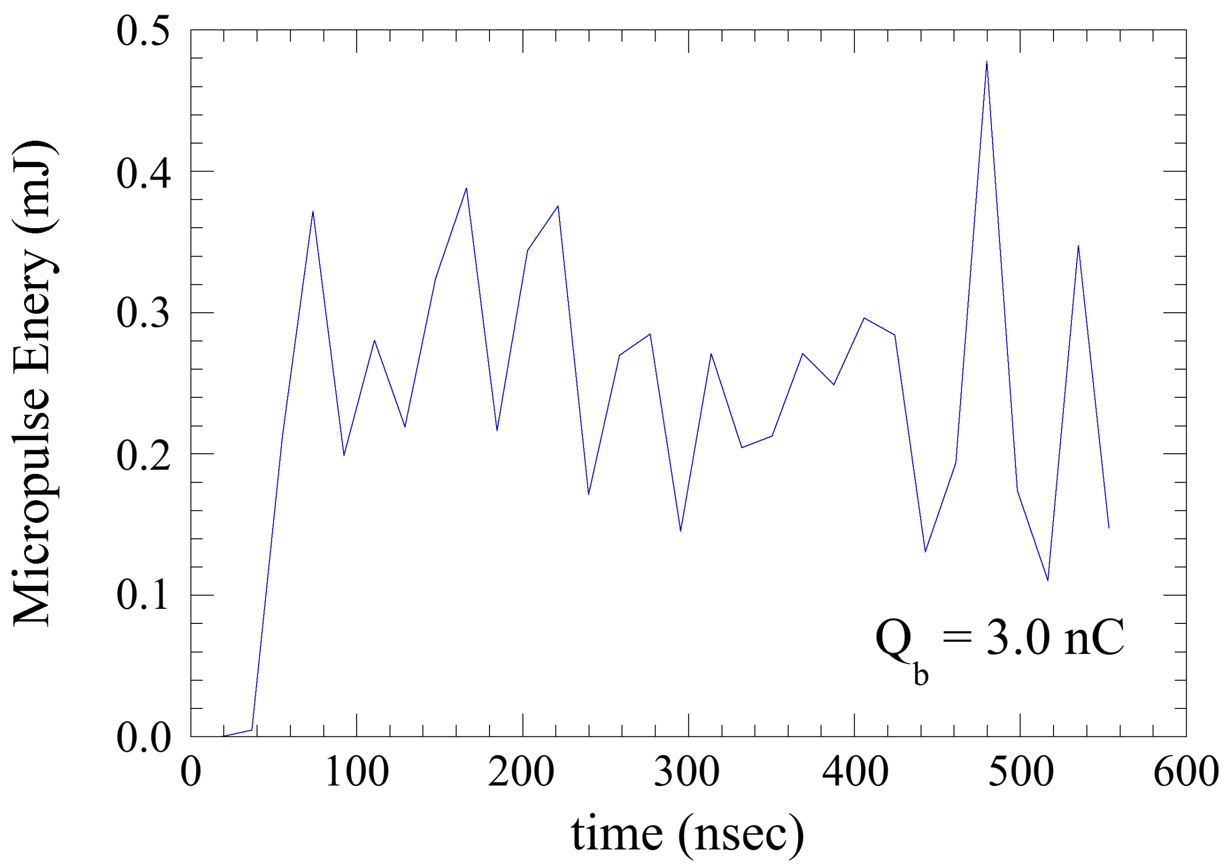
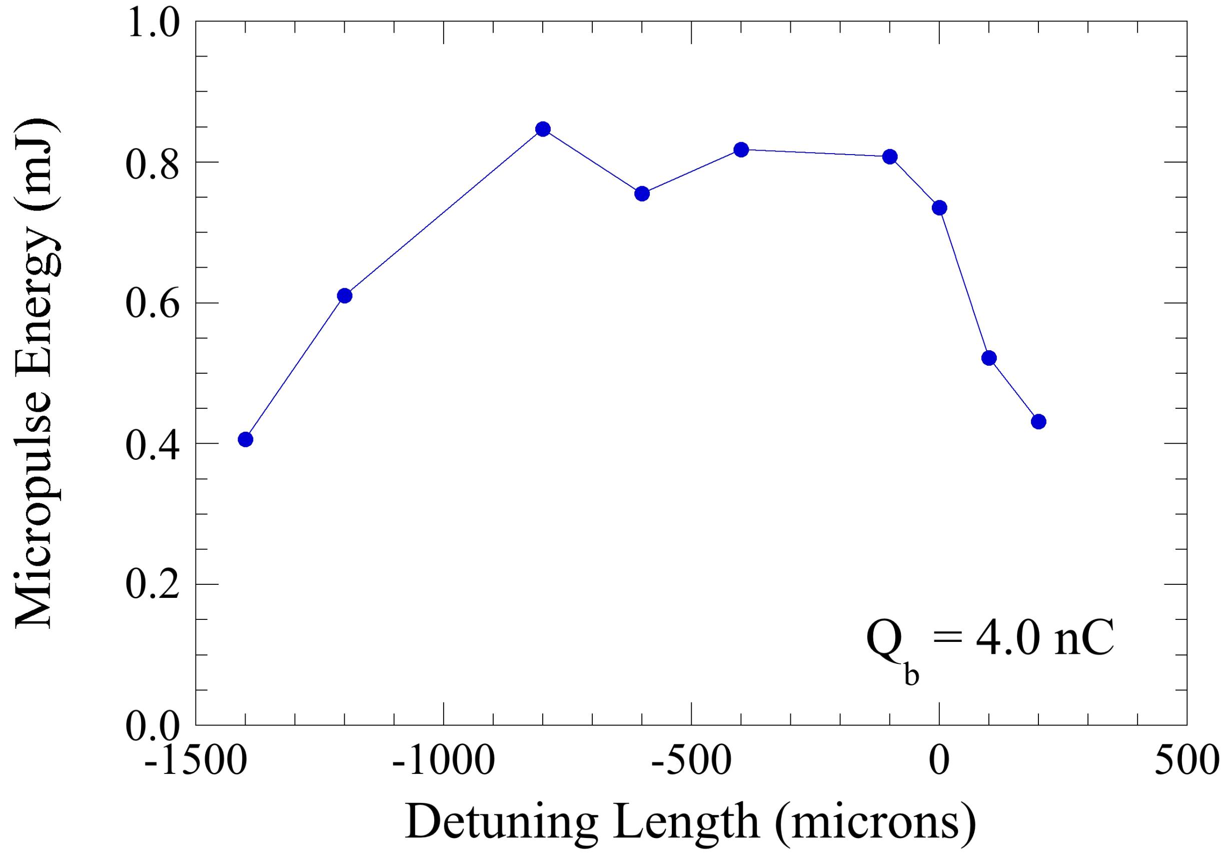
OSCILLATION RISE TIME

- The round-trip time in the resonator at zero-detuning is 18.45 nsec
- The rise time seen in the experiment to reach the steady-state was 100 – 150 nsec
  - Reasonable agreement with simulation results



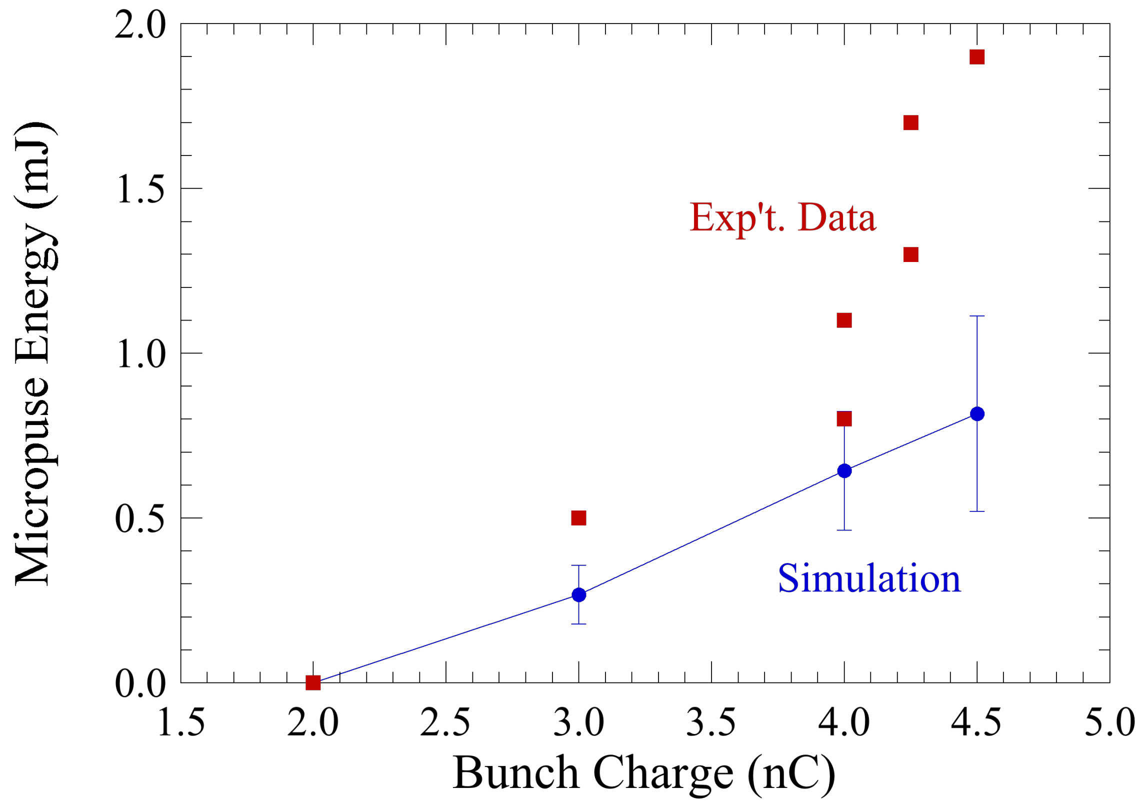
CAVITY DETUNING

- The detuning length observed in the experiment was ≈ 2000 microns
  - The simulations are in reasonable agreement with the experiment



OUTPUT POWER vs BUNCH CHARGE

- The variation in micro-pulse output power is also in reasonable agreement with experiment up to about 4.0 nC
  - Need to study the effect at high bunch charge more closely
  - The data were obtained nominally at zero-detuning



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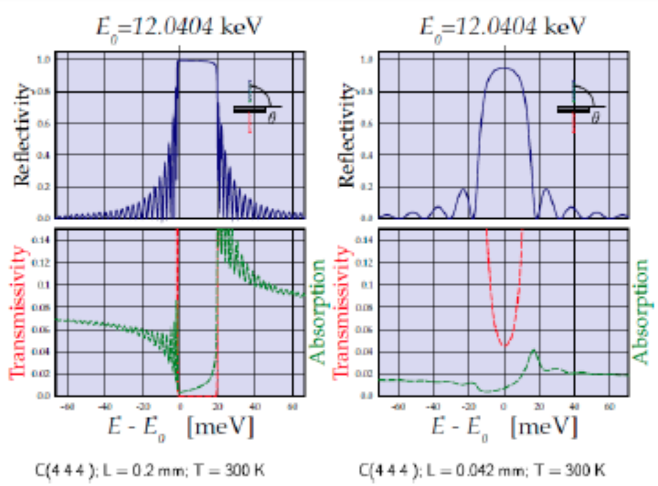
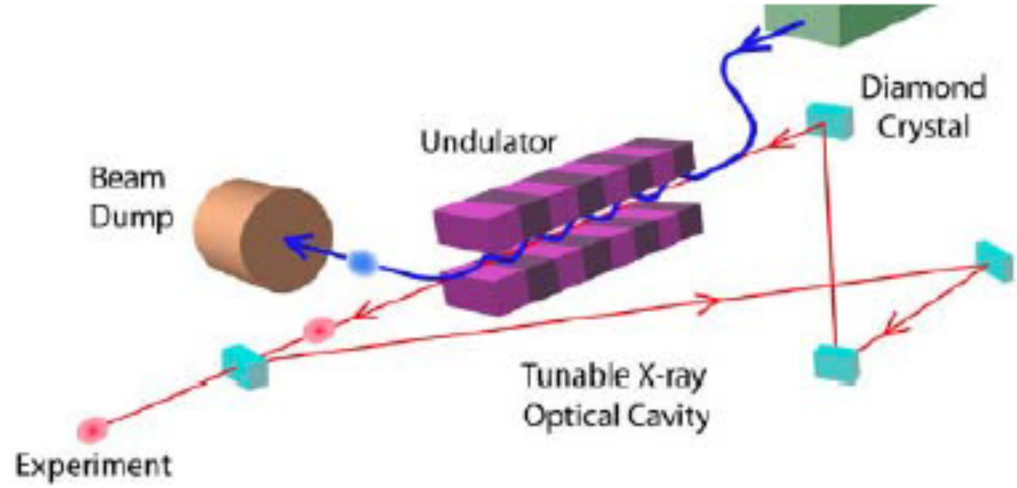
A NOTIONAL X-RAY OSCILLATOR

- K.-J. Kim presented a notional XFELO at the Future Light Source Workshop at SLAC in March 2010
  - Low-gain/high-Q oscillator
    - high reflectivity mirrors
  - Diamond crystal Bragg cavity



Courtesy: Y. Shvyd'ko



- Electron Beam
  - 7 GeV/20 pC/1 psec/1 MHz/20 A
  - 0.2 mm-mrad/2 × 10^{-4}
- Wiggler
  - 2.0 cm/60 m/7 – 8 kG
- L_G > 200 m → low gain regime

- Resonator
  - 2 or 4 diamond crystal Bragg reflectors
  - 12 keV/1.033 Å
  - Total reflectivity ≈ 85%

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A NOTIONAL X-RAY RAFEL

- We can adapt the Bragg cavity from the XFELO design
  - Need only 10% total reflectivity
  - Out-couple/loss of 90% of the power
- Electron Beam
  - 12 GeV/100 pC/30 fsec/3333 A
  - 0.2 mm-mrad/5 × 10^{-5}
- Wiggler
  - 2.0 cm/15 kG
- Ming Xie's parameterization
  - 0.885 Å/14 keV
  - P_{noise} = 1660 W → $L_w \approx 30$ m
  - P_{sat} = 27.4 GW
  - L_G = 1.98 m
  - L_{sat} = 37.3 m
- The synchronous repetition rate, $f_{rep} = c/L_{cav}$
  - $L_{cav} \approx 100$ m → $f_{rep} \approx 3$ MHz

SUMMARY & CONCLUSIONS

- The RAFEL has advantages for both high-power & short-wavelength FELs
  - High out-coupling means reduced mirror loading
  - Self-seeding for x-ray FELs

- An extensive discussion of the properties of a 2.2-μm RAFEL was given along with how it differs from a low-gain oscillator

- Preliminary comparisons between simulation and experiment were discussed for a 16.3-mm RAFEL experiment at LANL
  - Reasonable agreement found for simulations thus far

- A notional design for an x-ray RAFEL (14 keV) was discussed